Effects of Organic Dairy Manure on Soil Phosphatase Activity, Available Soil Phosphorus, and Growth of Sorghum-Sudangrass

Heidi M. Waldrip,[1] Zhongqi He,[2] and Timothy S. Griffin[3]

Abstract: Organic dairy (OD) production is increasing in the Northeastern United States due to consumer demand. Some physicochemical properties of OD manure differ from conventional dairy (CD) manure, which could influence nutrient cycling and soil fertility differently when OD manure is applied as fertilizer to meet plant N demands. Effects of OD manure on activities of acid phosphomonoesterase (ACP), alkaline phosphomonoesterase (ALP), phosphodiesterase (PDE), available soil phosphorus (P), and plant growth were investigated in a greenhouse study, where sorghum-sudangrass (*Sorghum bicolor* subsp. *drummondii*) was fertilized with manures from 13 organic dairies in Maine, CD manure, or NH_4NO_3. Soil phosphatase activities and modified Morgan P were determined at planting and after 16 weeks of plant growth. Plant growth did not differ ($P > 0.05$) when fertilized with OD and CD manures or inorganic fertilizer. However, there was a wide range in growth with OD manure, which was negatively correlated to manure C:N and C:P ($P < 0.05$) ratios. After 16 weeks, OD manure amended soils had higher modified Morgan P than soils with inorganic fertilizer ($P < 0.05$), but there was no difference between OD and CD manured soils ($P > 0.05$). Of the three soil phosphatases, ACP activity was highest and increased with OD manure similarly to CD manure. There was a negative correlation ($P < 0.01$) between ACP activity and manure C:P ratio, suggesting that manure C content influences P cycling and may reduce P availability in soils amended with OD manure, in a manner similar to CD manure.

Key words: Phosphatase, phosphorus availability, organic dairy manure, soil fertility, sudangrass.

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In response to consumer demand, the number of certified organic dairies and the production of organic dairy (OD) products in the United States have increased rapidly in recent years (Mayen et al., 2010; McBride and Greene, 2009). This is particularly true for the Northeastern United States, with Maine, Vermont, Pennsylvania, and New York ranking among the top 10 states for the number of organic farms (USDA NASS, 2008). Typically, organic dairies are managed differently than conventional dairies (CD) and include more pasture grazing and a higher proportion of forage-based feeds than their conventional counterparts (Novak and Fiorelli, 2010; USDA ERS, 2009). In addition, OD diets tend to contain less protein and energy from concentrates than CD diets due to the prohibitively high cost of organic grains (Hoshide et al., 2011; McBride and Greene, 2007). Other differences between OD and CD management are that dry litter must be provided in the rest area, and at least half of the total housing floor must be solid and not slatted or grid construction to be a certified OD dairy (Novak and Fiorelli, 2010), which would influence the manure carbon (C):phosphorus (P) ratios and other physicochemical properties involved in nutrient cycling and soil fertility.

The P in dairy manure exists in numerous inorganic and organic forms, including orthophosphate, pyrophosphate, phytate and other orthophosphate monoesters, orthophosphate diesters (phospholipids and DNA), and phosphonates (Toor et al., 2005; He et al., 2009). However, the specific animal diet influences the P forms in excreted manure due to both diet digestibility and P complexation with Fe, Al, Ca, and Mg in the digestive tract (Morse, 1992; Toor et al., 2005). Organic dairy management is necessarily reliant upon manure and compost as fertilizer sources for pastures and feedstuff crops; however, the manure (mixture of urine and feces) excreted by OD cows differs from that of CD cows (He et al., 2009; He and Ohno, 2012; He and Wang, 2012). Specifically, OD manure contains more soluble inorganic P and Ca/Mg-associated P, and less monoester P and stable metal phytate species, than CD manure (He et al., 2009). Furthermore, the soluble organic matter in OD manure contains more stable humic- and lignin-related components and less amino/protein N-related components than CD manure (He and Ohno, 2012). These differences may influence nutrient availability and the key biochemical processes involved in P cycling following application to soil. Availability of P for plant uptake following application of animal manure is influenced by microbial and chemical properties of the soil, manure composition, and rhizosphere processes (Dao et al., 2003; He et al., 2004, 2006a, 2006b; Waldrip et al., 2011). Manure application increases not only soil concentrations of total and soluble P, but also concentrations of specific P forms, including stable organic P moieties (Erich et al. 2002; Ylivainio et al. 2008; Waldrip-Dail et al. 2009). In-depth knowledge of factors affecting P availability of manures from different farm management systems is important to achieve optimal plant growth and to avoid negative environmental consequences following application of manure to meet plant N demands.

As organic P forms must be mineralized by phosphatases into inorganic P before plant uptake, soil biological activity and enzyme production related to organic P hydrolysis will affect P cycling (Magid et al. 1996). Three extracellular phosphatases involved in soil P cycling are acid phosphomonoesterase (ACP, EC 3.1.3.2), alkaline phosphomonoesterase (ALP, EC 3.1.3.1), and phosphodiesterase (PDE, EC 3.1.4). Both ACP and ALP are relatively nonspecific and can hydrolyze a range of low-molecular-weight P compounds, including mononucleotides, phytate, sugar phosphates, and polyphosphates, whereas PDE catalyzes the hydrolysis of nucleic acids and phospholipids (He and Honeycutt 2001; Turner et al. 2002). Although both root exudates and manure can stimulate phosphatase activity by providing soil microorganisms with sources of C, N, and P (Juma and Tabatabai 1977; Tarafdar and Jungk 1987), a negative-feedback mechanism partially controls phosphomonoesterase activity, and enzyme inhibition can occur when high levels of inorganic P are present (Colvan et al., 2001; Olander and Vitousek, 2000). Phosphatases can also affect environmental quality following mismanagement of manure, as soluble P in surface runoff is related to organic P content and phosphatase activity (Yu et al., 2006).

Low P availability due to metal complexation has been shown to be a constraint to sorghum-sudangrass growth under both greenhouse and field conditions (Fernandes and Coutinho, 1999; Hyde and Morris, 2004). Because of higher concentrations of Ca/Mg-associated P in OD manure than in CD manure (He et al., 2009), it is of interest to evaluate the bioavailability of the P in OD manure. Furthermore, OD manure amendment could influence soil phosphatase activities and other microbially mediated P transformations differently than CD manure due to higher levels of soluble inorganic P, lower levels of monoester P, and the presence of more humified and lignin-related organic matter in OD manure (He et al., 2009; He and Ohno, 2012).

In an aerobic laboratory incubation study, He et al. (2006b) investigated the P dynamics in soils that received one of 11 different dairy manures applied at a target N rate. These researchers (He et al., 2006b) concluded that growers converting from conventional to organic practices (i.e., where manure is the sole source of N and P) may estimate bioavailable P in manure to meet their short-term P needs; however, it was suggested that further studies were needed to determine if similar results would be obtained when growing plants were present. As a continuation of the work of He et al. (2006b), we adopted a similar design for this study, where the objectives were to evaluate the effects of OD manure applied on an N basis on soil phosphatase activities, available soil P concentrations, and the growth of sudangrass under greenhouse conditions. These data were compared with those from soils amended with equivalent N rates of inorganic N fertilizer and CD manure.

MATERIALS AND METHODS

Soil and Manures

Manure samples were collected from 13 commercial dairy farms under organic management in Maine. In addition, one sample was collected from a commercial farm under conventional management. Selected management information and manure properties are listed in Table 1. On the OD farms, cows received forage-based diets of hay, haylage, and corn (*Zea mays*) silage. In addition, most OD farms incorporated pasture grazing as a feeding strategy. The majority of the manure samples were solid and contained sawdust bedding. After collection, manure samples were homogenized, air dried, ground to pass 2 mm, and stored at −20°C until use.

Soil was collected from the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) research site at Newport, Maine (0–20 cm, Bangor silt loam, coarse-loamy, mixed, frigid, Typic Haplorthod), sieved (6 mm) while still field moist, and air dried. Selected soil properties were determined by the Maine Agricultural and Forestry Experiment Station soil testing laboratory using standard methods (Gee and Bauder 1986; Hoskins 1997). Specific soil properties were as follows: 42% sand, 6% clay, 4.4% organic matter, 2.52% total C, and 2.5 mg kg^{-1} modified Morgan P, and 122 mg kg^{-1} modified Morgan K. The soil contained 2.0 g kg^{-1} total N, with 55% of total N as NH_4^+ and 44% as organic N. Soil pH was 5.2 (1:1 soil to water), and cation exchange capacity was 4.8 cmol (+) kg^{-1}. Manure P was determined on a TJA Model IRIS 1000 inductively coupled plasma-optical emission spectrometer (Thermo Elemental, Franklin, MA) following microwave-assisted HNO_3/HCl digestion (EPA Method 3051). Manure Kjeldahl N was measured following digestion (Scarf, 1998) on a Labconco macro Kjeldahl unit (Labconco, Kansas City, MO), and ammonia-N determined colorimetrically following distillation on a flow injection analyzer (Latchat Instruments, Loveland, CO). Selected chemical properties of the manures are listed in Table 2.

Greenhouse Experiment

This study was conducted from February to June 2008, in a greenhouse using natural lighting conditions. Dairy manure was added to soil at a rate of 143 mg total N kg^{-1}. The current experiment was part of a larger study intended to investigate N mineralization following OD amendment; therefore, the experimental design included a control (no manure) that contained 143 mg N kg^{-1} from ammonium nitrate (NH_4NO_3). The amounts of P, C, organic N, and NH_4^+-N added to soil through each dairy manure application are presented in Table 3. To increase aeration, soil was mixed with sand at a mass ratio of three parts soil to one part sand (dry weight). Aliquots of 2.0 kg (soil/sand plus appropriate manure or inorganic fertilizer N) were placed in 6-in-diameter pots, gravimetrically moistened to 60% water-filled pore space with distilled water, and packed to a bulk density of approximately 1.2 Mg m^{-3}. There were three replicate pots per treatment. One pot per treatment contained a Watermark soil moisture sensor (The Irrometer Company, Inc., Riverside, CA) connected to a Watch Dog 450 data logger (Spectrum Technologies, Inc., Plainfield, IL) for monitoring soil water tension, air temperature, and relative humidity. Pots were preincubated for 7 days on a greenhouse bench. Any emerging weeds were removed using forceps. Following preincubation, the pots were gravimetrically brought up to 45% water-filled pore space with distilled water.

After preincubation, sorghum-sudangrass (*Sorghum bicolor* subsp. *Drummondii*) was planted at a depth of 12.5 mm. Upon emergence, seedlings were thinned and transplanted to ensure three evenly spaced, healthy plants per pot. Soil moisture was maintained at near-field capacity (10 kPa), and pots were rotated on the greenhouse bench. Plant aboveground biomass was harvested by cutting every 5 weeks, leaving about 7.6 cm of residue on each plant. The harvested plant material was oven dried at 65°C for 48 h, and dry biomass was determined gravimetrically. Soil samples were collected for analysis of enzyme activity at planting and after 16 weeks of plant growth. Soils were sieved (2 mm) and stored at 4°C in plastic bags until analysis.

Phosphatase Activities

Acid phosphomonoesterase, ALP, and PDE activities were determined using a modification of the methods of Tabatabai and Bremner (1969). Specifically, 0.1 g field-moist soil (<2-mm

TABLE 1. Selected Management Information and Manure Properties of 13 Organic Dairies (OD) and a Conventional Dairy

Manure	Forage	Bedding	Storage	Manure Type
OD1	Hay, Pasture	Hay, sawdust	Stacking Pad	Solid
OD2	Hay, pasture, haylage, corn silage	Sawdust, sand	Pit	Solid
OD3	Hay, haylage	Sawdust, shavings	Pad	Solid
OD4	Hay, haylage	N/A†	Pad	Solid
OD5	Hay, pasture, haylage	Green sawdust	Pit	Solid
OD6	Hay, pasture	Sawdust	Roofed storage	Solid
OD7	Hay, pasture, haylage	Sawdust	Bedded pad	Solid
OD8	Hay, haylage	Sawdust	Stacking pad	Solid
OD9	Hay, pasture, haylage	Sawdust	Stacking pad	Solid
OD10	Hay, haylage	Sawdust, shavings	Stack windrows	Solid
OD11	Hay, haylage	Sawdust, shavings	Stack windrows	Solid
OD12	Hay, haylage	Sawdust	Pad	Solid
OD14	N/A	N/A	Pit	Semisolid
Conventional dairy	N/A	N/A	N/A	Solid

†N/A, no information available.

sieve) was incubated with 0.4 mL modified universal buffer containing 6 μL of toluene at either pH 6.5 (ACP) or pH 11.0 (ALP) and 0.1 mL of 0.05 M *p*-nitrophenol phosphate solution for 1 h at 37°C on an incubator-shaker at 250 revolutions/min. All incubations were performed in triplicate. Following incubation, 0.1 mL of 0.5 M $CaCl_2$ and 0.4 mL of 0.5 M NaOH were added, and the resulting suspension centrifuged at 14,000 × *g* for 2 min. The supernatant was then removed with a pipette and analyzed by UV-Vis spectroscopy for *p*-nitrophenol released (*p*-NP) at a wavelength of 400 nm. Soil- and substrate-free controls were included. Activity of PDE was determined in a similar manner at pH 8.0, using *bis-p*-nitrophenol phosphate (*bis-p*-NP) as the substrate.

Statistical Analysis

The experiment was arranged in a completely randomized design with three replications per treatment. Single-factor analysis of variance was used to examine the effects of manure treatment on plant growth, phosphatase activities, and soil P. Repeated-measures analysis with a pairwise *t* test was used to examine changes in variables over time. Correlation analysis was used to identify relationships between variables, and significance was determined using Pearson product-moment correlation coefficients. All statistical analyses were conducted with Systat Version 13.0 (Systat Software, Inc., Chicago, IL).

RESULTS AND DISCUSSION

Manure Properties

Total P in the OD manures ranged from 2.0 to 18.7 g kg^{-1}, with a mean of 5.2 g kg^{-1} (Table 2). Most of the values fell within the ranges for total P listed in the USDA Agricultural Waste Management Handbook, where total P in dairy manure is

TABLE 2. Selected Properties of 13 Organic Dairy Manures and a Conventional Dairy Manure

Manure	DM (%)	C	N	C:N	P†	C:P	Organic N	NH_4^+−N
		% DM			g kg^{-1}		g kg^{-1}	
OD1	24	38.0	2.79	13.6	18.7	20.3	16.5	11.5
OD2	22	29.8	1.71	17.4	4.5	66.2	10.0	4.0
OD3	19	40.2	2.11	19.1	5.4	74.4	19.9	5.4
OD4	19	41.7	1.49	30.0	5.8	71.9	14.3	4.2
OD5	16	41.5	1.46	28.4	4.4	94.3	9.5	5.7
OD6	21	34.9	1.82	19.2	5.2	67.1	13.9	3.3
OD7	30	45.4	0.88	51.6	2.0	227.0	6.0	3.7
OD8	23	41.2	1.49	27.7	2.6	158.5	11.7	3.0
OD9	20	41.5	1.41	29.4	4.5	92.2	13.3	1.0
OD10	20	42.2	1.44	29.3	3.4	124.1	12.3	2.9
OD11	20	43.2	1.28	33.8	3.5	123.4	12.8	2.5
OD12	19	43.1	1.42	30.4	4.9	88.0	13.8	6.3
OD14	20	40.2	2.44	16.5	2.4	167.5	12.9	7.9
Mean (SD)‡	21 (3)	40.2 (3.9)	1.67 (0.50)	26.5 (9.6)	5.2 (4.2)	106 (54)	12.9 (3.3)	4.7 (2.7)
Conventional dairy	15	36.8	1.34	27.5	6.9	53.3	18.7	4.1

†Phosphorus and nitrogen data are presented on a dry matter basis.
‡SD from the mean.

TABLE 3. Amount of Nutrients Added to Soil When Organic (OD) and Conventional Dairy (CD) Manures Were Applied at a Total N Rate of 143 mg kg^{-1}

Manure	P	C	Total N	Organic N	NH_4^+-N
	mg kg^{-1}				
OD1	96	2056	143	85	59
OD2	45	3141	143	103	40
OD3	31	2406	143	113	30
OD4	45	3417	143	110	33
OD5	42	4117	143	89	54
OD6	43	3073	143	115	28
OD7	30	7107	143	89	54
OD8	26	4251	143	114	29
OD9	45	4405	143	133	10
OD10	32	4209	143	115	28
OD11	32	4272	143	120	23
OD12	35	3248	143	98	45
OD14	16	2930	143	89	54
Mean (SD)[†]	40 (19)	3,741 (1262)	143 (0)	106 (15)	37 (15)
Conventional dairy	44	2443	143	117	26
Inorganic fertilizer	—	—	143	—	72

[†]SD from the mean.

between 4.4 and 6.9 g kg^{-1} (USDA-NRCS, 1999). For CD manure, total P was 6.9 g kg^{-1}, which is not significantly different from that of OD manures ($P > 0.05$). The mean C content of the OD manures was 40.2% and ranged from 29.8% to 45.4%. Total N in OD manure was 1.67% ± 0.50% and was not different from CD manure ($P > 0.05$). There was a high degree of variability in the NH_4^+-N content of the OD manures, ranging from a low of 1.0 g kg^{-1} for OD9 to a high of 11.5 g kg^{-1} for OD1. Some of the lowest values came from farms that stored manure in windrows (Table 1, OD10 and OD11), indicating that this storage method could increase NH_3 losses by volatilization. CD manure contained 4.1 g kg^{-1} NH_4^+-N (Table 2).

In contrast to NH_4^+-N concentrations, the organic N contents of the OD manures were very similar, with a mean value of 12.9 ± 3.3 g kg^{-1}. Manure from CD had a higher concentration of organic N than most OD manures, containing 18.7 g kg^{-1}. There was a wide range in C:N ratios for the OD manures, with a low of 13.6 for OD1 and a high of 51.6 for OD7. The C:N ratio of the CD manure was 27.5 and was not different from the mean C:N ratio of OD (26.5 ± 9.6). Similarly, there was a large degree of variability in the C:P ratios of the OD manures, with a range of 20.3 to 227 and a mean of 106 ± 54. The C:P ratio of CD manure was 53.3. The large differences observed in C:N and C:P ratios between the OD manures were likely a reflection of the amount and type of bedding used and losses of C and N from manure storage systems (Table 1).

Plant Biomass

Despite large differences in the amounts of NH_4^+-N and P added when manures were applied at rate of 143 mg total N kg^{-1} (Table 3), there was no significant ($P > 0.05$) difference in total aboveground biomass production (sum of three cuttings) between sudangrass plants that received inorganic fertilizer, any of the OD manures, or CD manure (Fig. 1). In addition, there was no difference in total plant biomass production between plants that received any of the OD manures and the CD manure. The average dry biomass production with OD manure was 4.07 ± 1.09 g pot^{-1}, and ranged from 2.18 to 5.76 g pot^{-1}. Overall, the plants that received OD1 had the greatest biomass production (5.76 g pot^{-1}), which was significantly ($P < 0.05$) greater than plants fertilized with OD7, OD9, OD10, and OD11. There were differences in early biomass production (first cut). As an example, plants that received OD10 produced only 0.33 g biomass per pot at first cut, which was 82% less than plants that received OD1, and significantly lower than plants that were fertilized with 10 of the 13 OD manures and CD manure. It should be noted that the OD1 manure had a very high total P concentration (Table 2), and plants fertilized with OD1 received more P (96 mg kg^{-1}) and NH_4^+-N than plants fertilized with other OD manures or CD manure (Table 3). The biomass production by sudangrass was consistent with that observed in a similar study by Fernandes and Coutinho (1999). They noted that despite the addition of up to 150 mg kg^{-1} of soluble P from calcium phosphate, P complexation with Al constrained plant growth in soils with pH of 5.3 to 5.5, which is very close to the soil pH in the current study (pH 5.2).

Correlation analysis showed that total biomass production was negatively related to the amount of OD manure C applied ($r = -0.521$, $P < 0.001$), manure C:N ratio ($r = -0.476$, $P < 0.01$), and manure C:P ratio ($r = -0.324$, $P < 0.05$) and positively related to NH_4^+-N applied ($r = 0.504$, $P < 0.01$) and OD manure P applied ($r = 0.341$, $P < 0.05$) (Table 4). Overall, the strongest positive relationship between plant growth and manure properties was between early biomass production (first cut) and manure NH_4^+-N applied ($r = 0.649$, $P < 0.001$), whereas the strongest negative relationship was between manure C applied and second cut biomass ($r^2 = -0.626$, $P < 0.001$). Plant biomass production at first cut differed between some OD manures (Fig. 1) and was positively correlated with manure P applied ($r^2 = 0.378$, $P < 0.05$) (Table 4), indicating that the P in OD manure is available for plant uptake.

The nonsignificant findings of the effects of OD manure on total biomass production as compared with inorganic fertilizer N or CD manure are consistent with those of Waldrip et al.

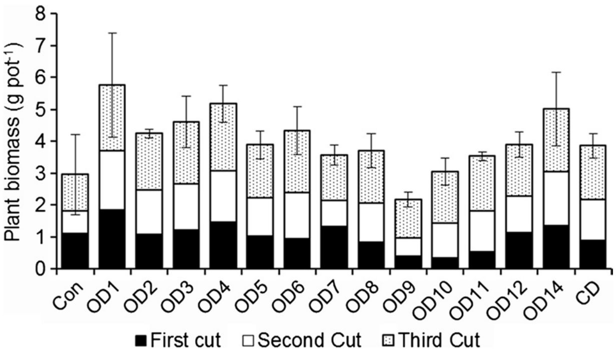

FIG. 1. Plant aboveground biomass production by sudangrass grown in soil amended with inorganic fertilizer N (Con), 13 OD manures, and manure from a CD. Plant tissue was harvested by cutting at 5-week intervals. Error bars represent ± SD for total biomass production.

(2011), where it was observed that poultry manure amendment increased early growth of perennial ryegrass (*Lolium perenne*), but there was no statistically significant difference in biomass production between plants that received inorganic fertilizer and poultry manure after 16 weeks of growth. In addition, Leytem et al. (2011) saw no difference in silage corn growth between soil fertilized with CD manure and inorganic fertilizer. In the current study, it is clear that both OD and CD manures are comparable to inorganic fertilizer in supplying nutrients for sudangrass growth throughout a growing season in soil, when applied at equivalent N rates to a soil that is not P-limiting.

Available Soil P

The modified Morgan soil P test was developed to estimate the capacity of a soil to supply P to plants and is the recommended test for soils with a predominance of aluminum phosphates, such as the soils in the Northeastern United States (Wolf and Beegle, 2011). At planting, there was no difference ($P > 0.05$) in modified Morgan P between soils that received inorganic fertilizer, any OD manure, or CD manure (Fig. 2). However, after 16 weeks of plant growth, there was a higher modified Morgan P concentration in soils that received any manure treatment (OD manures and CD manure) than inorganic fertilizer. The highest soil P followed application of OD1 with 3.59 mg kg^{-1} of modified Morgan P. In most cases, available soil P was lower after 16 weeks of plant growth than at planting.

Correlation analysis indicated that, at planting, modified Morgan P was positively related to the amount of OD manure P applied (r = 0.363, $P < 0.050$) and negatively related to the manure C:P ratio (r = −0.325, $P < 0.05$) (Table 4). After 16 weeks of plant growth, modified Morgan P was highly related to the amount of OD manure P applied (r = 0.849, $P < 0.001$) and to total plant biomass production (r = 0.441, $P < 0.01$), whereas there was a negative relationship with OD manure C:P ratio (r = −0.590, $P < 0.001$), OD manure C:N ratio (r = −0.353, $P < 0.05$), and amount of OD manure C applied (r = −0.347, $P < 0.05$).

The environmental and agronomic threshold beyond which no further P application is recommended for Maine soils is 20 mg kg^{-1} modified Morgan P (Sharpley et al., 2003). Therefore, despite the large differences in N:P ratios of the OD manures (Table 2), none of the OD manure treatments in this study resulted in excessive P accumulation when applied at equivalent N rates (Fig. 2).

He et al. (2004) applied CD manure to two soils in an aerobic incubation study and noted a transformation of P forms that was largely driven by soil properties. Specifically, soluble inorganic and organic P from CD manure was rapidly converted to less available P forms (e.g., P sorbed onto crystalline surfaces such as the exteriors of Al and Fe oxides or carbonates) (He et al., 2004). Therefore, the soluble inorganic P in OD manure could be transformed into metal-P complexes or immobilized into microbial biomass, leading to a temporal decrease in plant-available P. Higher levels of Al/Fe-associated P in the rhizosphere are correlated with plant biomass production (Waldrip

TABLE 4. Relationships Between Plant Biomass Production, Nutrients Applied With Organic Dairy Manures, Available Soil P, and Activities of Acid Phosphomonoesterase, Alkaline Phosphomonoesterase, and Phosphodiesterase at Planting (Init), and After 16 Weeks of Sudangrass Growth (Final)

Parameter	Manure C Applied	Manure P Applied	Manure C:N	Manure C:P	Manure NH_4^+-N Applied	Manure Organic N Added
	Correlation coefficient, r†					
Available soil P_{init}‡	−0.009	0.363*	−0.006	−0.325*	−0.066	0.058
Available soil P_{final}	−0.347*	0.849***	−0.353*	−0.590***	0.196	−0.197
ACP_{init}	−0.187	0.234	−0.044	−0.304	−0.338*	0.339*
ACP_{final}	−0.406*	0.593***	−0.388*	−0.477**	0.102	−0.097
ALP_{init}	0.268	−0.116	0.369*	0.193	0.049	−0.050
ALP_{final}	0.285	−0.033	0.252	0.105	−0.249	0.245
PDE_{init}	0.302	0.383*	0.245	0.076	0.323	−0.325*
PDE_{final}	0.075	0.177	0.135	−0.217	0.070	−0.077
1st-Cut biomass	−0.286	0.378*	−0.240	−0.182	0.649***	−0.644
2nd-Cut biomass	−0.626***	0.293	−0.595***	−0.370*	0.381*	−0.378*
3rd-Cut biomass	−0.540***	0.207	−0.498**	−0.353*	0.232	−0.231
Total biomass	−0.521***	0.341*	−0.476**	−0.324*	0.504**	−0.501**

†Significant at $P < 0.05$ (*), 0.01 (**), 0.001 (***); n = 39.

‡Modified Morgan soil P.

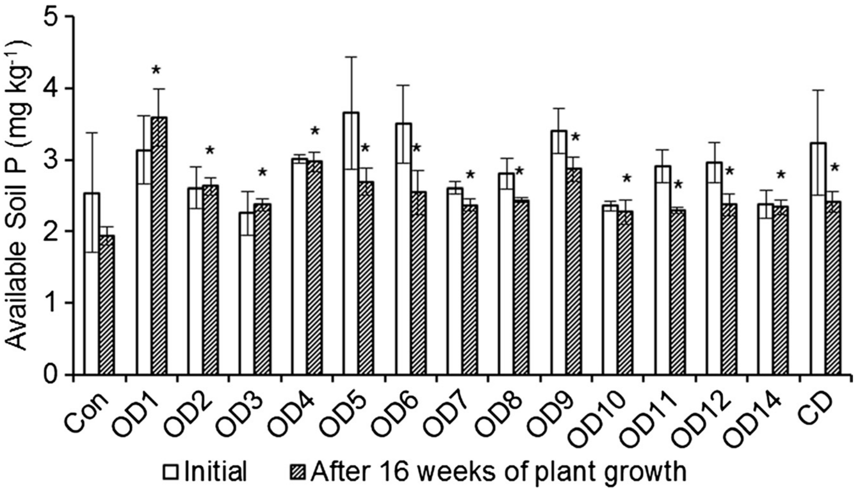

FIG. 2. Modified Morgan P in soil at planting and after 16 weeks of sudangrass growth when soil was amended with inorganic fertilizer N (Con), 13 OD manures, and manure from a single CD. An asterisk (*) indicates significant difference ($P < 0.05$) from Con treatment at a particular soil sampling time.

et al., 2011) and could become available during the growing season as plant roots promote transformation of metal-P complexes by excretion of chelating agents that increase P solubility (Hinsinger, 2001).

Previous studies have reported that additions of C from CD manure influence soil P availability, and a negative relationship exists between manure C:P ratio and soil test P (Olsen P) (Leytem and Westermann, 2005; Leytem et al., 2011). Specifically, when manures with higher C:P ratios are applied, the concentrations of labile and moderately labile P in soil tend to decrease. This relationship was assumed to be due to higher microbial activity following the addition of C, leading to immobilization of soil P into microbial biomass (Leytem et al., 2005, 2011). The negative relationship observed between both initial and final soil modified Morgan P content and manure C:P in the current work indicates that the C:P ratio of OD manure is an important indicator of P availability for crop uptake, in a manner similar to CD manure.

Phosphatase Activities

Activity of ACP was the highest of all the three enzymes tested, with initial rates averaging 150.0 ± 46.5 mg *p*-NP kg^{-1} h^{-1} for OD manure treatments (Fig. 3A). Both OD and CD manure amendments resulted in greater ACP activity at planting than inorganic fertilizer, with average increases of 117% for OD manure and 101% for CD manure. Of the OD manures, 11 of the 13 samples resulted in higher initial rates of ACP activity than inorganic N fertilizer. The highest ACP activity was observed with OD10, with 224 mg *p*-NP kg^{-1} h^{-1}. Interestingly, this high ACP activity with OD10 corresponded with the lowest first-cut biomass production (Fig. 1), suggesting that perhaps low levels of available P in OD10 during early plant growth resulted in production of root-borne ACP or stimulation of extracellular soil ACP activity by rhizosphere processes to meet plant nutrient demands. For inorganic fertilizer treatment, ACP activity increased over time ($P < 0.05$) and after 16 weeks of plant growth was 109% higher than initial values. In contrast, only five of the 13 OD manures had a significant increase in ACP activity over time ($P < 0.05$), and only three of the OD manures had final ACP activity that was significantly higher than the inorganic fertilizer treatment ($P < 0.05$).

Correlation analysis showed that ACP activity at planting (ACP_{init}) was negatively related to the amount of OD NH_4^+-N applied ($r = -0.338$, $P < 0.05$). Final ACP activity (ACP_{final}) was most highly correlated with the amount of manure P applied ($r = 0.593$, $P < 0.001$), followed by manure C:P ratio ($r = -0.477$, $P < 0.01$), manure C applied ($r = -0.406$, $P < 0.01$), and manure C:N ratio ($r = -0.388$, $P < 0.05$).

The findings of this study are in contrast to those of a previous study, where poultry manure amendment had little effect on ACP activity (Waldrip et al., 2011); however, in the previous study (Waldrip et al., 2011), soil ACP activity was higher than the current study, with an average activity of 323 mg *p*-NP kg^{-1} h^{-1}. In a field study, Marinari et al. (2000) found that fertilization of corn plots with stabilized dairy manure increased ACP activity almost threefold, which was attributed to a priming effect for mineralization of native soil OM and subsequent release of soluble nutrients for microbial growth. It is difficult to make strong inferences about the relationship between manure C:P ratios and ACP activities in the current study, because while there was a trend for manures with higher C:P ratios to have lower ACP activity, some OD manures (e.g., OD6 with a C:P ratio of 67.1) had very low ACP activity.

Alkaline phosphatase (ALP) activity at planting ranged from 43.7 (inorganic fertilizer N) to 87 mg *p*-NP kg^{-1} h^{-1} (OD8) (Fig. 3B). Average initial ALP activity for the OD manures was 61.9 ± 18 mg *p*-NP kg^{-1} h^{-1}, which was not different ($P > 0.05$) from CD manure (65.2 ± 15.8 mg *p*-NP kg^{-1} h^{-1}) or inorganic fertilizer N (43.7 ± 4.0 mg *p*-NP kg^{-1} h^{-1}). Only OD8 had initial ALP activity that was significantly different from inorganic fertilizer N, with a 101% increase. After 16 weeks of plant growth, six of the 13 manures had higher ALP activity than inorganic fertilizer N ($P < 0.05$). However, in general, ALP activity did not change significantly over time, with the exception of soil amended with OD6 and OD9, which had ALP activity that was slightly higher than initial rates ($P < 0.05$). Alkaline phosphatase activity was not well correlated to most of the OD manure variables, showing only a slight positive relationship with manure C:N ratio ($r = 0.369$, $P < 0.05$).

Previously, Waldrip et al. (2011) noted that initial ALP activity with poultry manure amendment was negatively

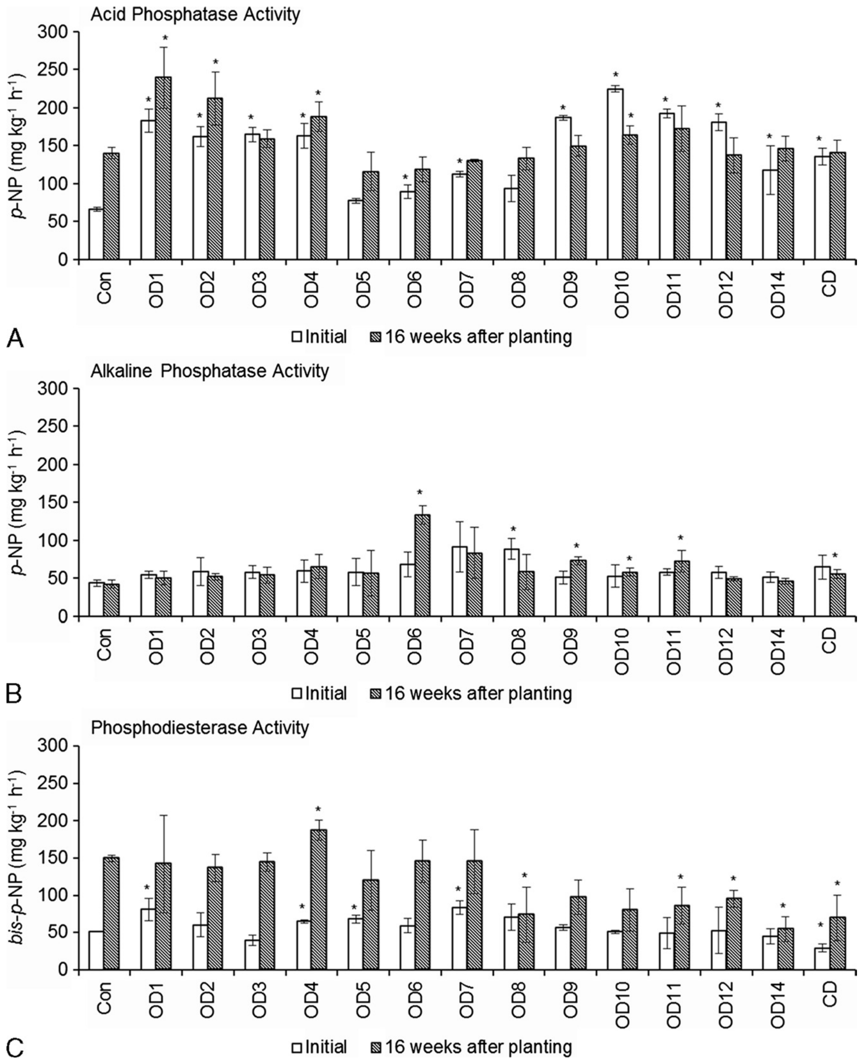

FIG. 3. Activities of (A) acid phosphomonoesterase, (B) alkaline phosphomonoesterase, and (C) phosphodiesterase in soil at planting and after 16 weeks of sudangrass growth when soil was amended with inorganic fertilizer N (Con), 13 OD manures, and manure from a CD. An asterisk (*) indicates significant difference ($P < 0.05$) from Con treatment at a particular soil sampling time.

correlated to soil P content. However, when growing ryegrass plants were present, poultry manure had little effect on ALP activity, despite a strong correlation between rhizosphere ALP activity and Ca-associated inorganic P (Waldrip et al., 2011). Other researchers have reported that CD manure application increased ALP activity in soil under silage corn (*Z. mays*) and that ALP activity increased linearly with manure P application rate (Leytem et al., 2011). However, in the current study, this same relationship was not observed. As an example, the OD1 treatment received the most P (96 mg P kg^{-1}), whereas the OD14 received the least (16 mg P kg^{-1}); however, there was no clear difference between ALP activity with these two manures (Fig. 3B)

Phosphodiesterase activity with OD manure averaged 60.3 ± 12.9 mg *bis-p*-NP kg^{-1} h^{-1} at planting, which was higher than with CD manure (29.4 ± 5.6 mg *bis-p*-NP kg^{-1} h^{-1}, $P < 0.05$), but not different from inorganic fertilizer N (51.0 ± 0.42 *bis-p*-NP kg^{-1} h^{-1}, $P > 0.05$) (Fig. 3C). Of the 13 OD manures, five treatments had initial PDE activities that were higher than with inorganic fertilizer. The PDE activity with CD manure was lower than with inorganic fertilizer ($P < 0.05$). The highest initial PDE activity was observed with OD7 and was 84 mg *bis-p*-NP kg^{-1} h^{-1}. The general trend for inorganic fertilizer, OD manure, and CD manure was an increase in PDE over time; however, there was a high degree of variability in measured final PDE activities in manured soils. After 16 weeks of plant growth, six of the 13 OD treatments had higher PDE activity than soil that received inorganic fertilizer ($P < 0.05$). The average final PDE activity for OD manure was 116 ± 38 mg *bis-p*-NP kg^{-1} h^{-1}, and the highest was 188 mg *bis-p*-NP kg^{-1} h^{-1} with OD4.

Similar to ALP, little correlation was found between PDE and OD manure variables (Table 4), with a positive relationship only between the amount of manure P applied ($r = 0.383$, $P < 0.05$). The PDE activities measured in this study were similar to those reported by our laboratory in an earlier work (Waldrip et al., 2011). In addition, the findings of increases in PDE activity with plant growth were consistent with the previous study. As PDE can be produced by plant roots as well as microorganisms and is affected by rhizosphere processes (Chen et al. 2002; Tarafdar and Claassen 1988), our results suggest that OD manure has little effect on soil PDE activity.

In this study, ACP, ALP, and PDE activities were within the range reported by other research groups (Chen et al. 2002; Colvan et al. 2001; Yu et al. 2006). As in the current study, Chen et al. (2004) also found that ACP activity predominates over ALP activity when soil pH is less than 7.0. It has been suggested that ACP is important for maintaining the balance of soil solution P in response to plant uptake (Waldrip et al., 2011), and plant roots have been found to have the ability to produce only ACP in response to P deficiency (Colvan et al., 2001; Tarafdar and Claassen 1988).

Thus, we conclude that OD manure does not influence soil phosphatase activity, P cycling, or P availability differently than does CD manure when applied at equivalent N rates. This is despite large differences in the management of organic and CD farms and differences in the organic matter and P forms in the manures from the two systems. As with acidic soils fertilized with CD manure or other livestock manures, the hydrolysis of organic P forms is largely controlled by root- or microbial-borne ACP. Therefore, the information accumulated over years through research on CD manure could be used as a reference for predicting OD manure P availability and transformation in soils of the Northeastern United States. Further research is warranted to better understand the relationship between C:P ratios in dairy manure and microbial activity in manure-amended soils.

CONCLUSIONS

In summary, there was no difference in biomass production by sorghum-sudangrass plants fertilized with equivalent N rates from 13 OD manures, CD manure, or inorganic N fertilizer. After 16 weeks of plant growth, soils that received the OD manures had higher modified Morgan P than soils that received inorganic fertilizer; however, there was no difference in modified Morgan P concentration between soils that received OD or CD manures. Of the three major soil phosphatases, ACP had the highest activity, and OD manure increased ACP activity over inorganic fertilizer in a manner similar to CD manure. There was a strong negative correlation between ACP activity and OD manure C:P ratios, suggesting that high manure C content may influence P cycling and reduce P availability in soils amended with OD manure, in a manner similar to CD manure. We conclude that that best management practices and application rates typical for manure from CD are likely to be also appropriate for manures from under organic management; however, we caution that soil application of OD manures with high C concentrations, relative to N and P, may result in decreased soil fertility.

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